Band-Gap-Engineered Architectures for High-Efficiency Multijunction Concentrator Solar Cells

Richard R. King, A. Boca, W. Hong, X.-Q. Liu, D. Bhusari, D. Larrabee,
K. M. Edmondson, D. C. Law, C. M. Fetzer,
S. Mesropian, and N. H. Karam

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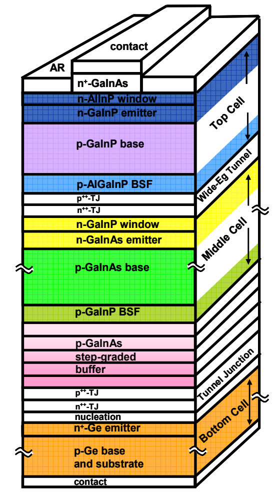
Thank You !

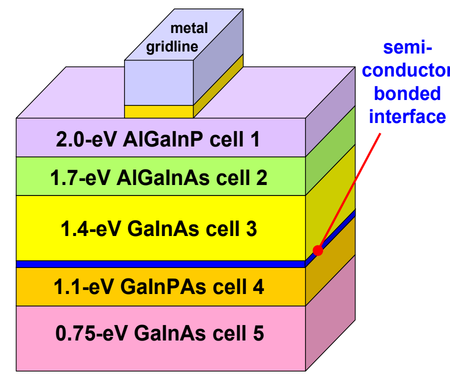
Outline

- **Solar cell theoretical efficiency limits**
  - Opportunities to change ground rules for higher terrestrial efficiency
  - Cell architectures capable of **>70%** in theory, **>50%** in practice



- **Metamorphic semiconductor materials**
  - Control of band gap to tune to solar spectrum

- **High-efficiency Multijunction terrestrial concentrator cells**
  - **Metamorphic (MM)** and **lattice-matched (LM)** 3-junction solar cells with ***>40%*** efficiency
  - ***4-junction*** MM and LM concentrator cells
  - Inverted metamorphic structure, semiconductor bonded technology (SBT) for MJ terrestrial concentrator cells



- **The solar resource and concentrator photovoltaic (CPV) system economics**

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High-Efficiency

Multijunction Cell

Architectures

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Maximum Solar Cell Efficiencies

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Measured **Theoretical**

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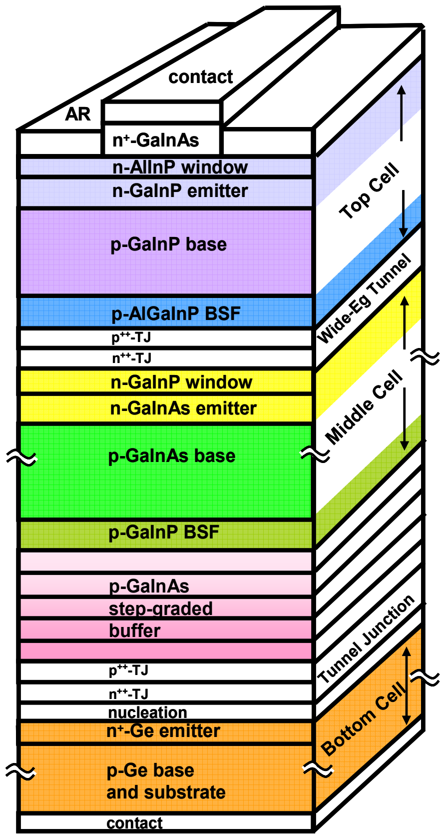
Measured:

- 3-gap GaInP/GaInAs/Ge LM cell, 364 suns (Spectrolab) **41.6%**
- 3-gap GaInP/GaInAs/Ge MM cell, 240 suns (Spectrolab) **40.7%**
- 3-gap GaInP/GaAs/GaInAs cell at 1 sun (NREL) **33.8%**
- 1-gap solar cell (silicon, 1.12 eV) at 92 suns (Amonix) **27.6%**
- 1-gap solar cell (GaAs, 1.424 eV) at 1 sun (Kopin) **25.1%**
- 1-gap solar cell (silicon, 1.12 eV) at 1 sun (UNSW) **24.7%**

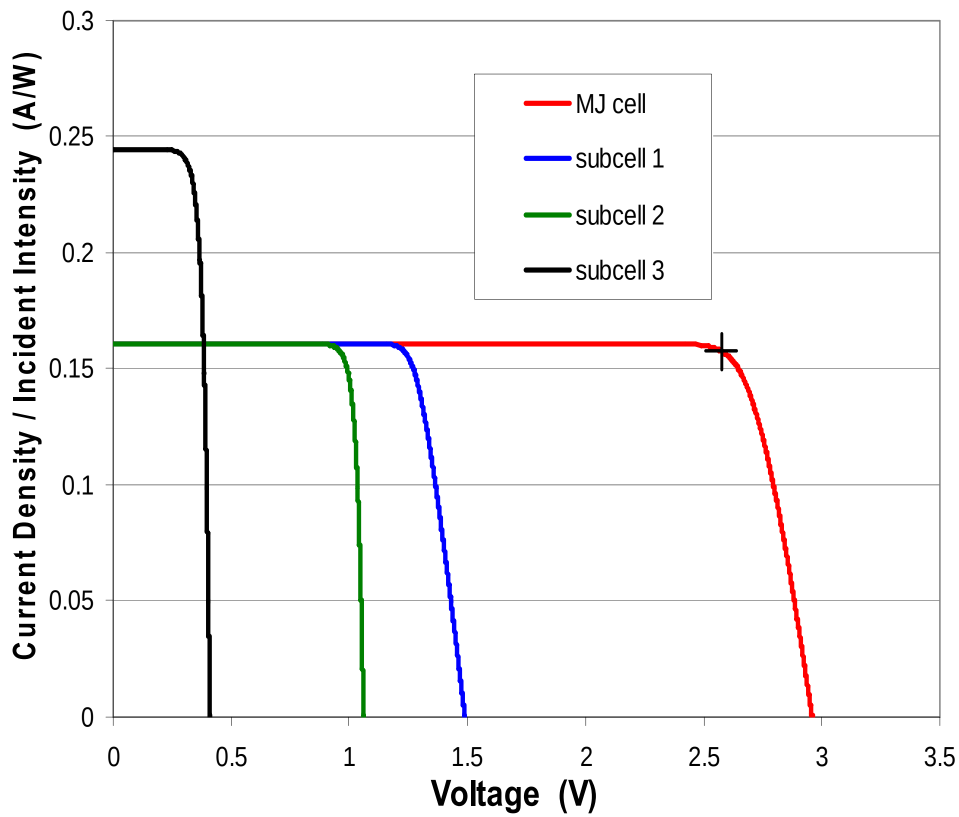
Theoretical:

- **95%** Carnot eff. = $1 - T/T_{sun}$ $T = 300$ K, $T_{sun} \approx 5800$ K
- **93%** Max. eff. of solar energy conversion
  $= 1 - TS/E = 1 - (4/3)T/T_{sun}$ (Henry)
- **72%** Ideal 36-gap solar cell at 1000 suns (Henry)
- **56%** Ideal 3-gap solar cell at 1000 suns (Henry)
- **50%** Ideal 2-gap solar cell at 1000 suns (Henry)
- **44%** Ultimate eff. of device with cutoff E_g: (Shockley, Queisser)
- **43%** 1-gap cell at 1 sun with carrier multiplication
  (>1 e-h pair per photon) (Werner, Kolodinski, Queisser)
- **37%** Ideal 1-gap solar cell at 1000 suns (Henry)
- **31%** Ideal 1-gap solar cell at 1 sun (Henry)
- **30%** Detailed balance limit of 1 gap solar cell at 1 sun
  (Shockley, Queisser)

Metamorphic (MM) 3-Junction Solar Cell



Lattice-Mismatched or Metamorphic (MM)



- Metamorphic growth of upper two subcells, GaInAs and GaInP

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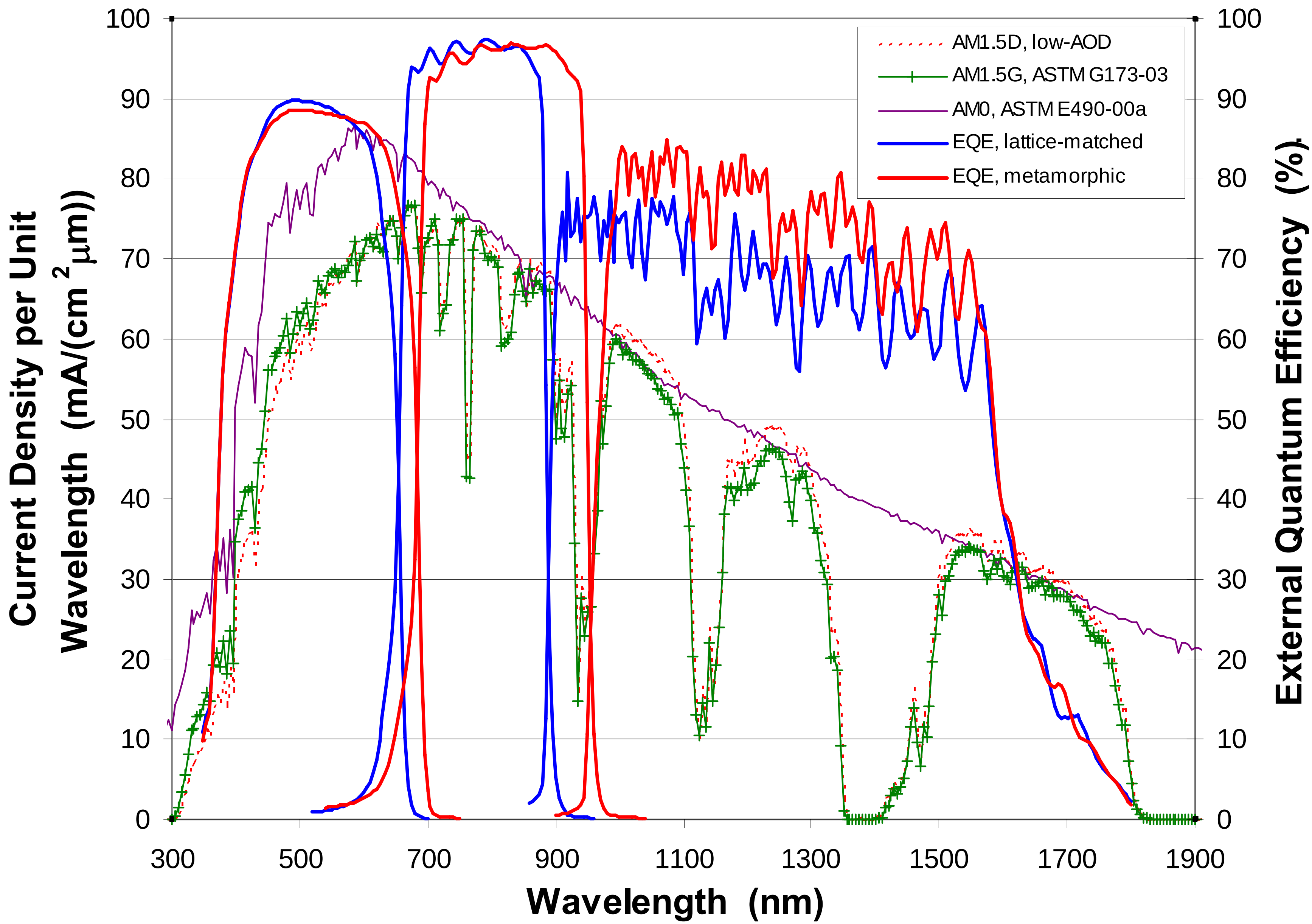
External QE of LM and MM 3-Junction Cells



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Metamorphic (MM) 3-Junction Solar Cell

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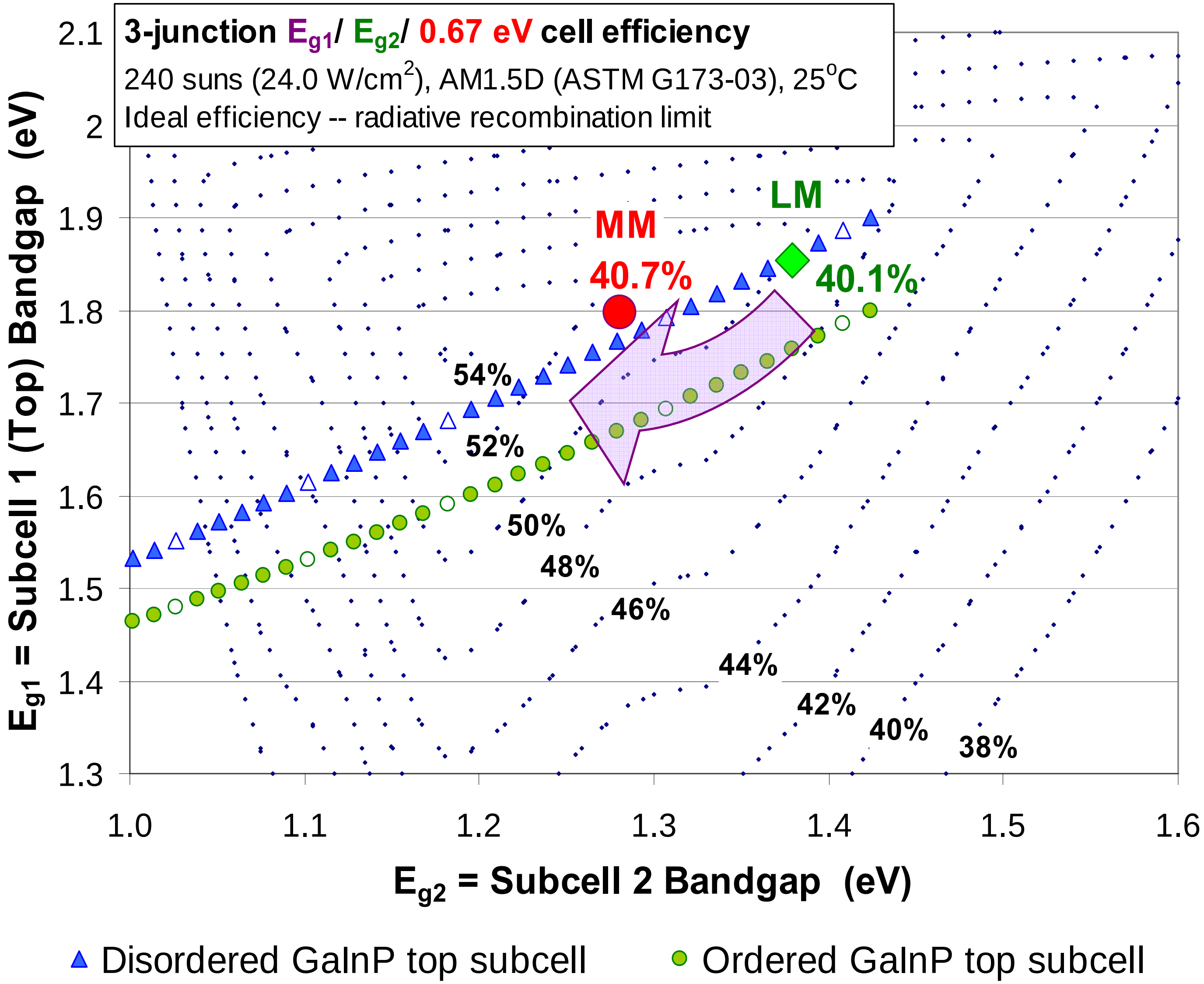

- Metamorphic GaInAs and GaInP subcells bring band gap combination closer to theoretical optimum

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Record 40.7%-Efficient Concentrator Solar Cell

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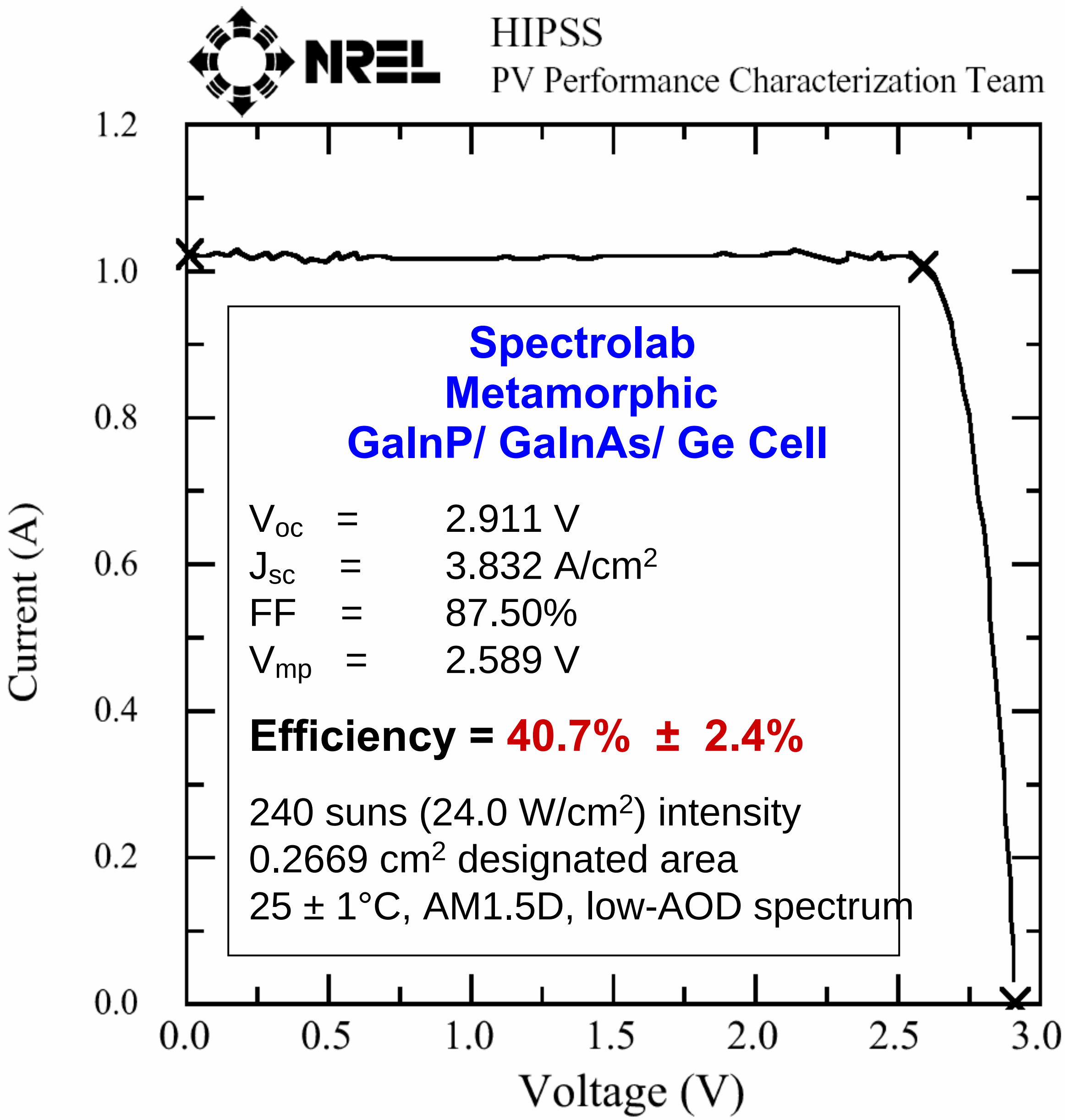
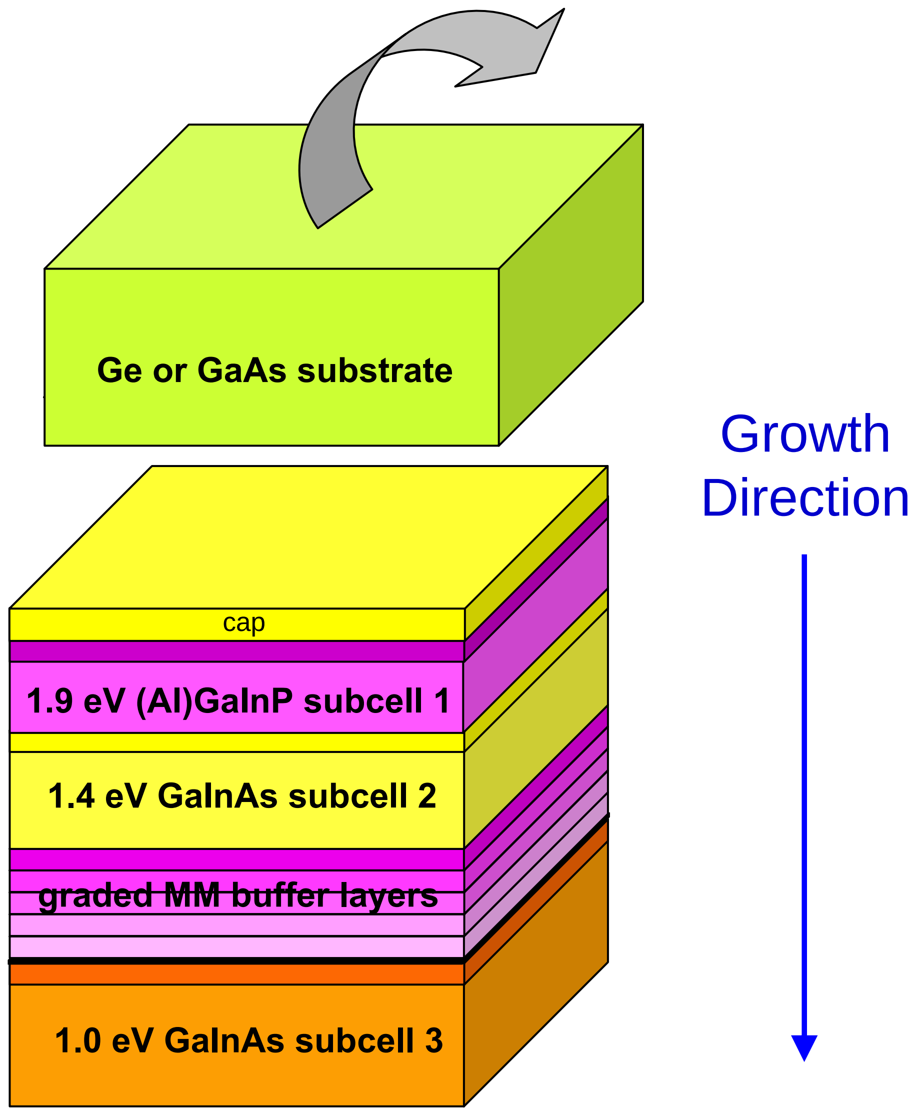


- **First solar cell of any type to reach over 40% efficiency**

Ref.: R. R. King et al., *"40% efficient metamorphic GaInP / GaInAs / Ge multijunction solar cells,"* Appl. Phys. Lett., ***90****, 183516, 4 May 2007.*

Concentrator cell light I-V and efficiency independently verified by J. Kiehl, T. Moriarty, K. Emery – NREL

Metamorphic (MM) 3-Junction Cells — Inverted 1.0-eV GaInAs Subcell



Growth on Ge or GaAs substrate, followed by substrate removal from sunward surface

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Inverted Metamorphic (IMM) 3-Junction Cell

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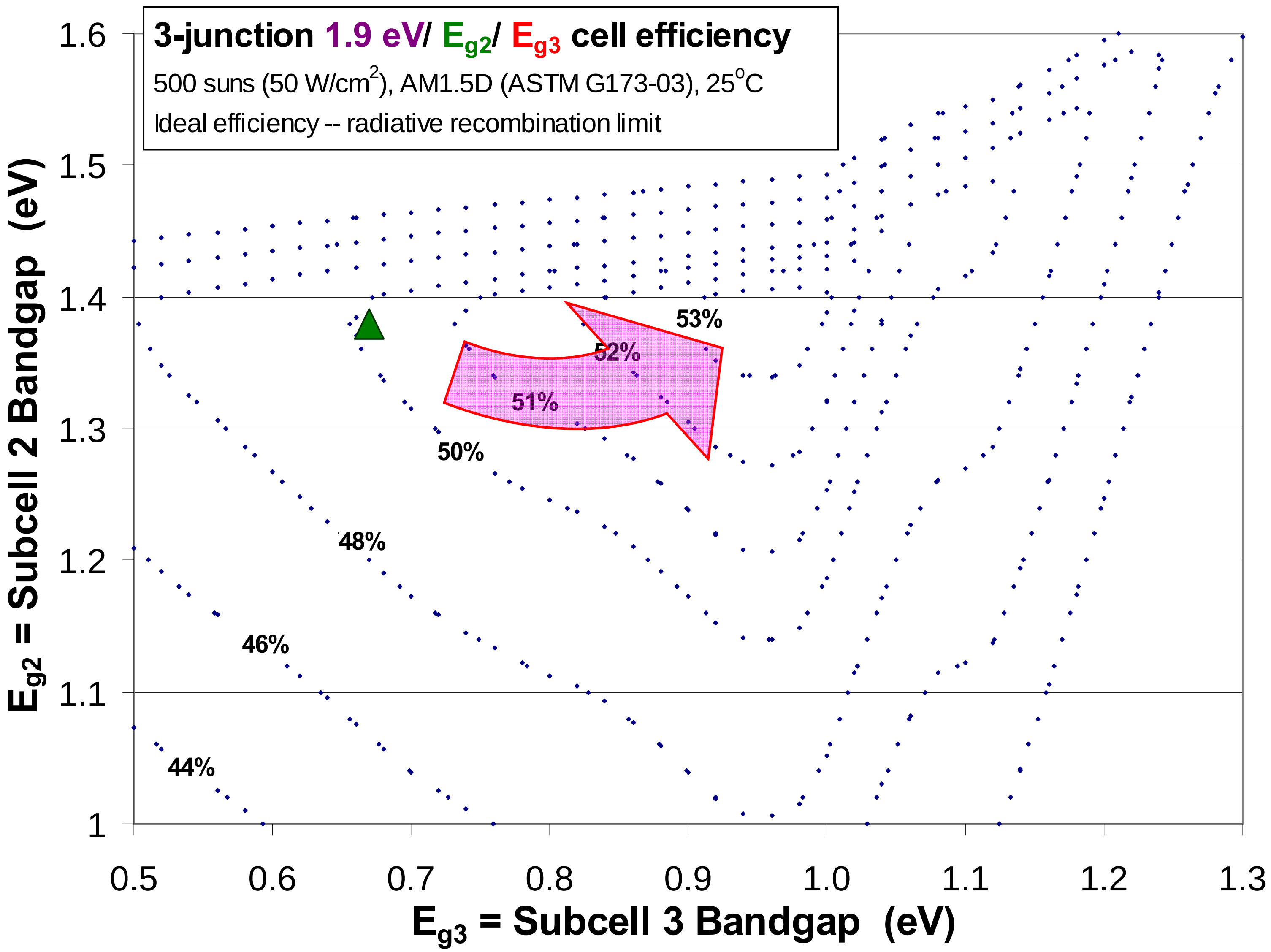

- Raising band gap of bottom cell from 0.67 for Ge to ~1.0 eV for IMM GaInAs raises theoretical 3J cell efficiency

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4-Junction Upright Metamorphic (MM) Terrestrial Concentrator Cell

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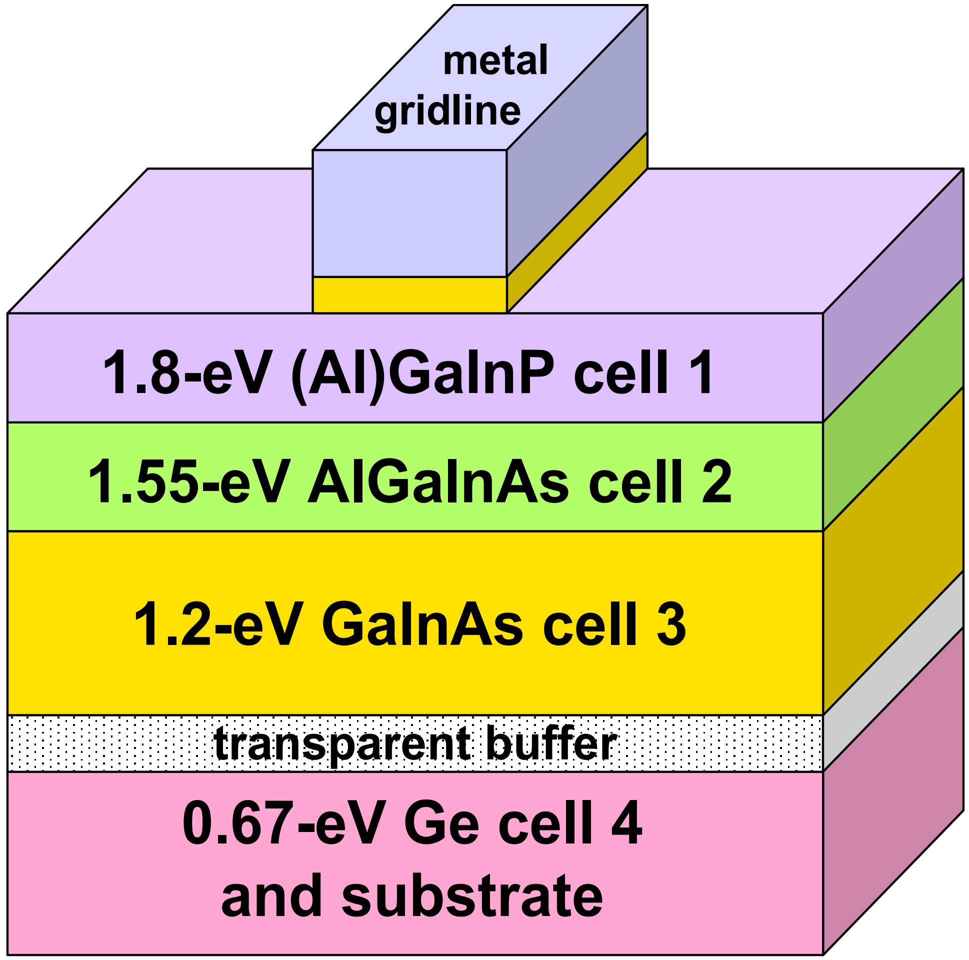

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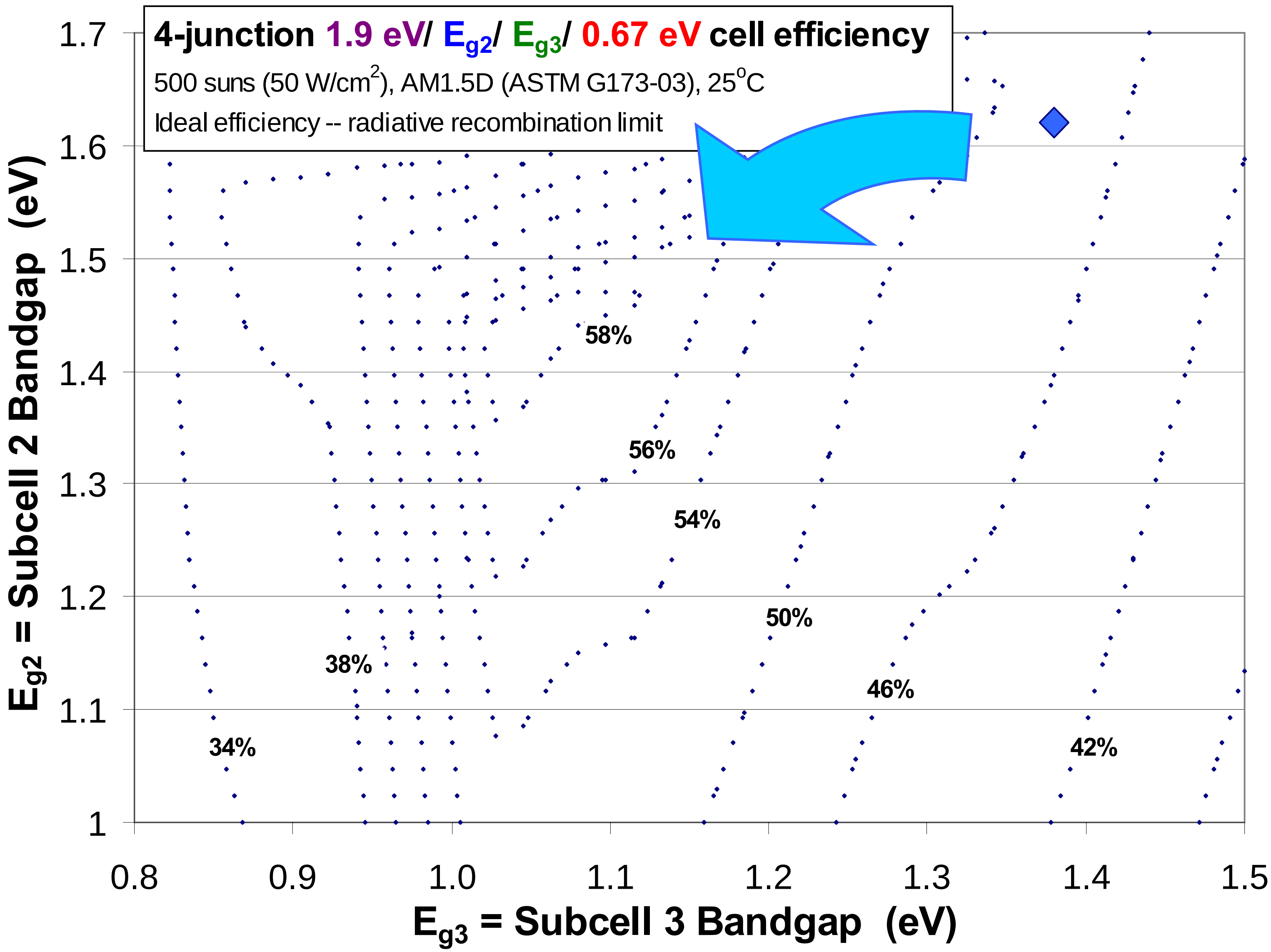
4-Junction Cell Optimum Band Gap Combinations



- Lowering band gap of subcells 2 and 3, e.g., with MM materials, gives higher theoretical 4J cell efficiency

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5-Junction Inverted Metamorphic (IMM) Cells

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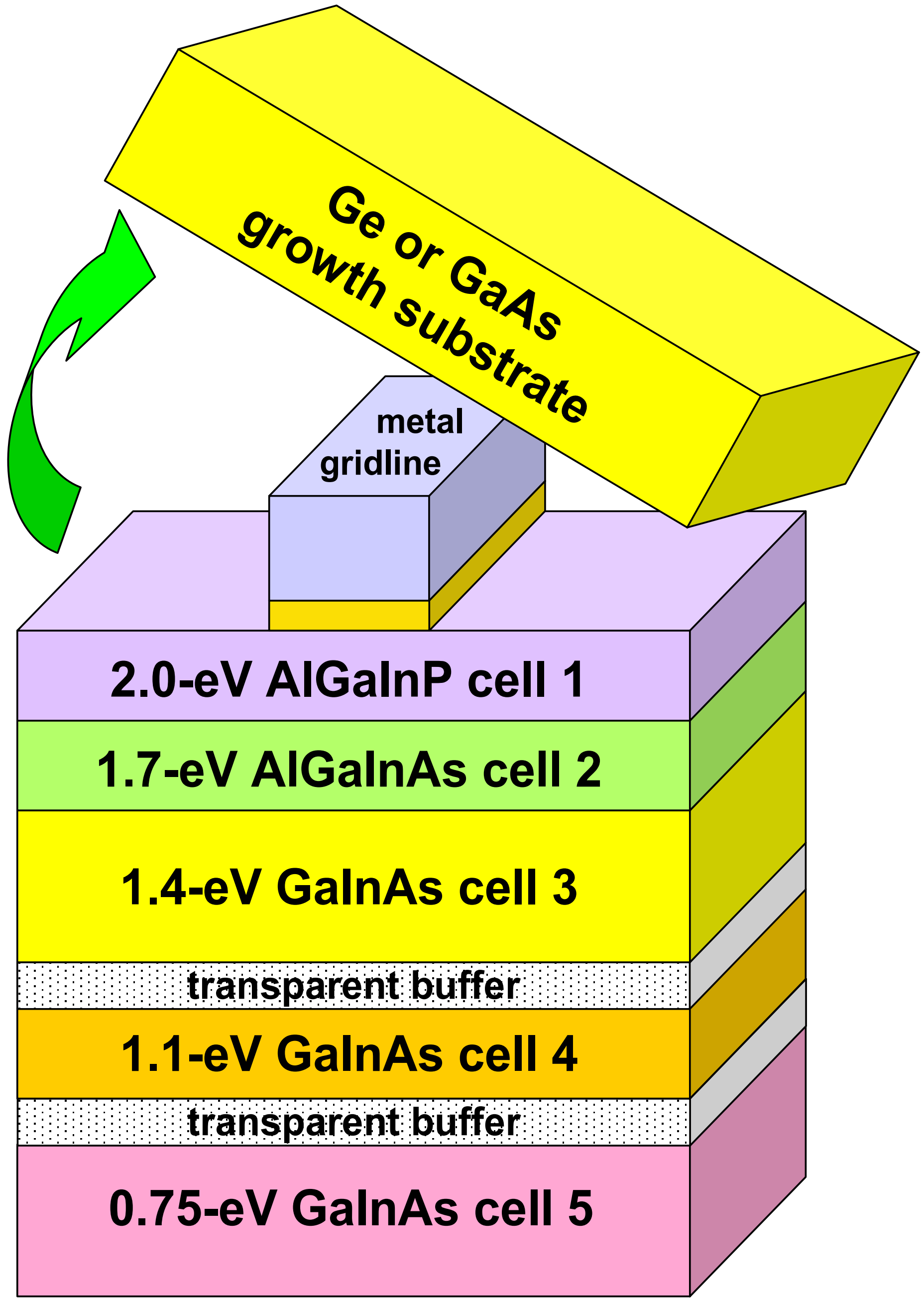

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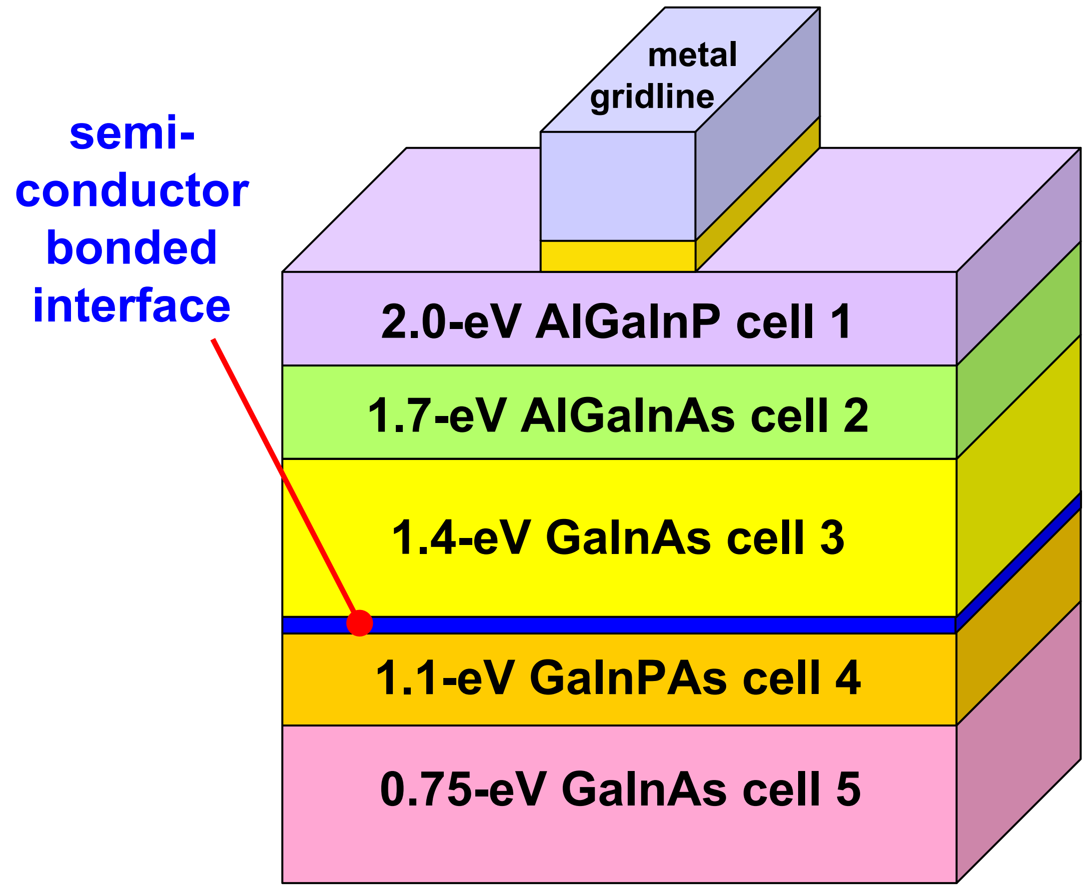
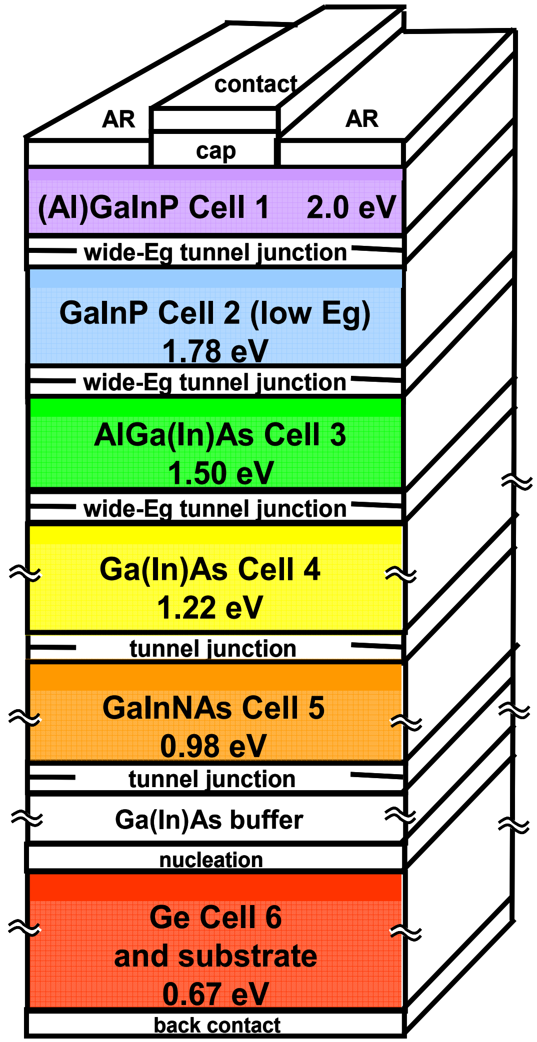
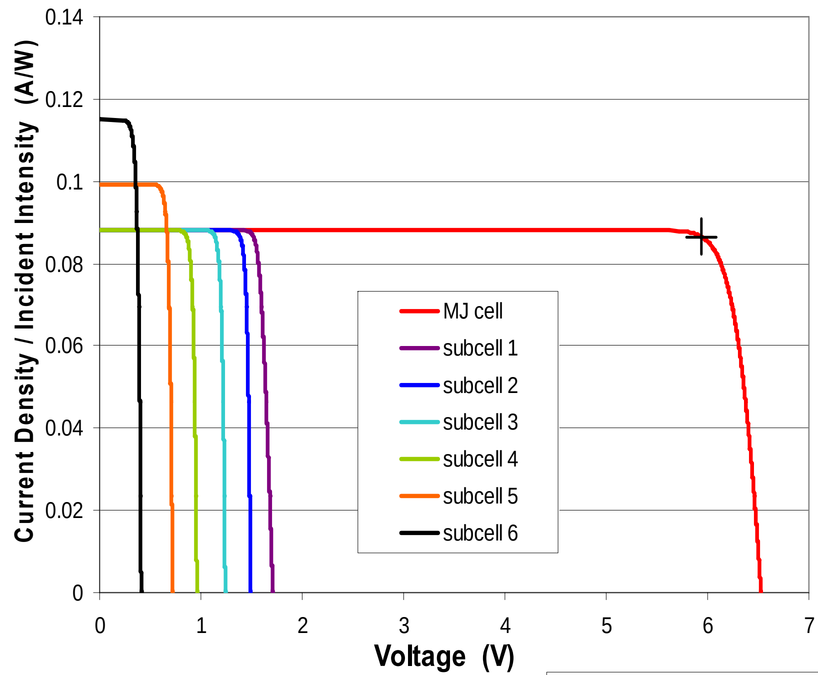
Semiconductor-Bonded Technology (SBT) Terrestrial Concentrator Cell

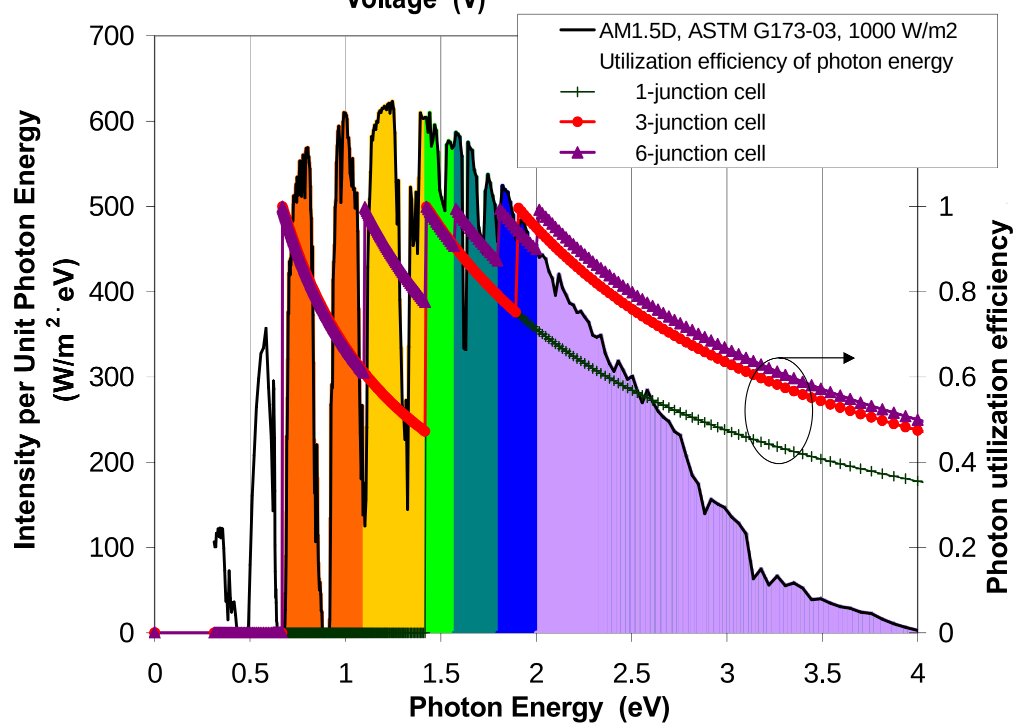
- **Wafer bonding for multijunction solar cells**
  - Low band gap cells for MJ cells using high-quality, lattice-matched materials
  - Epitaxial exfoliation and substrate removal
  - Formation of lattice-engineered substrate for later MJ cell growth
  - Bonding of high-band-gap and low-band-gap cells after growth
  - Electrical conductance of semiconductor-bonded interface
  - Surface effects for semiconductor-to-semiconductor bonding



6-Junction Solar Cells







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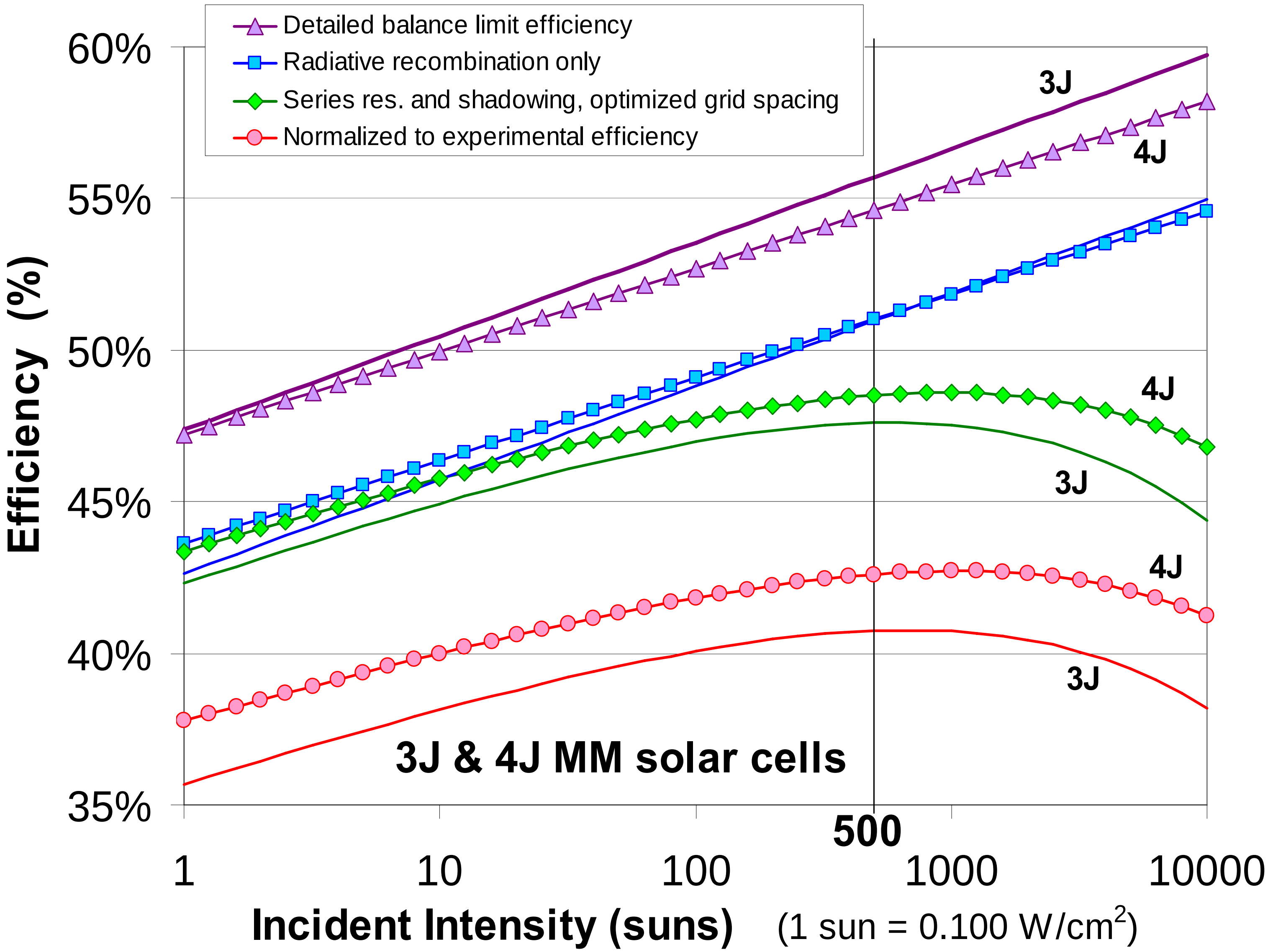
Modeled Terrestrial Concentrator Cell Efficiency



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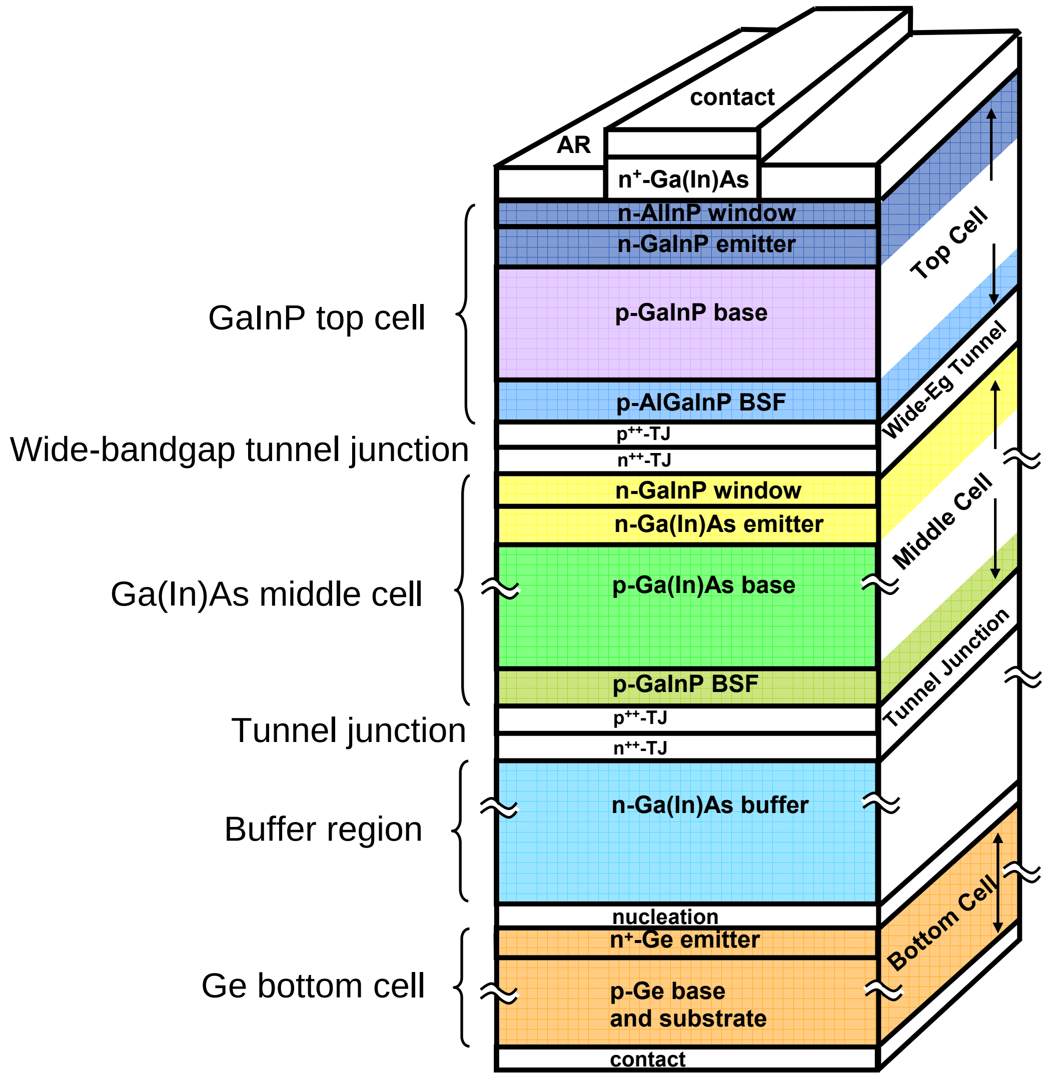
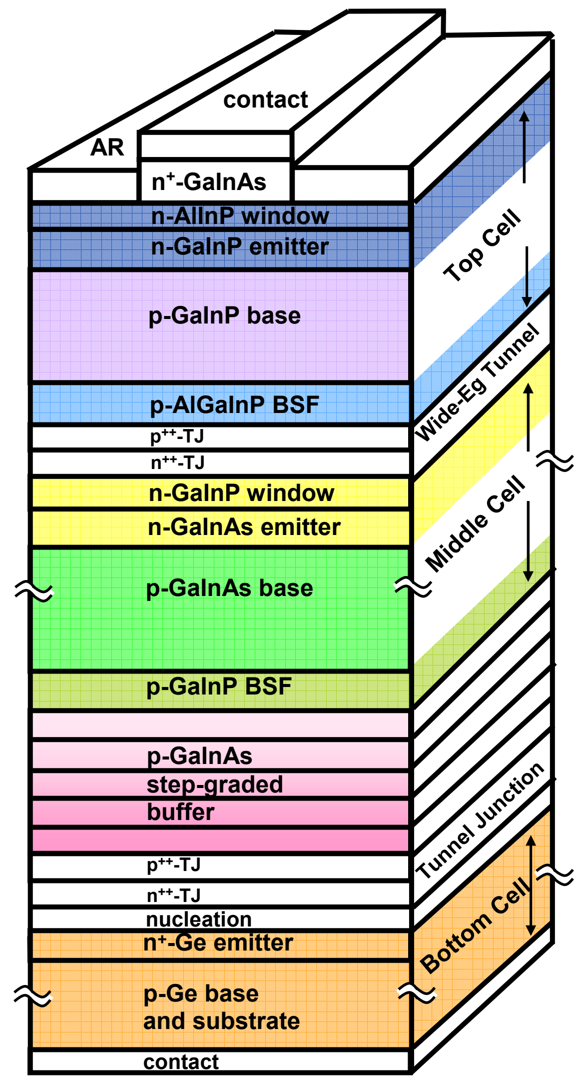
High-Efficiency Multijunction Cell Results

LM and MM 3-Junction Cell Cross-Section



Lattice-Matched (LM)



Lattice-Mismatched or Metamorphic (MM)

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New World Record
41.6% Multijunction Solar Cell

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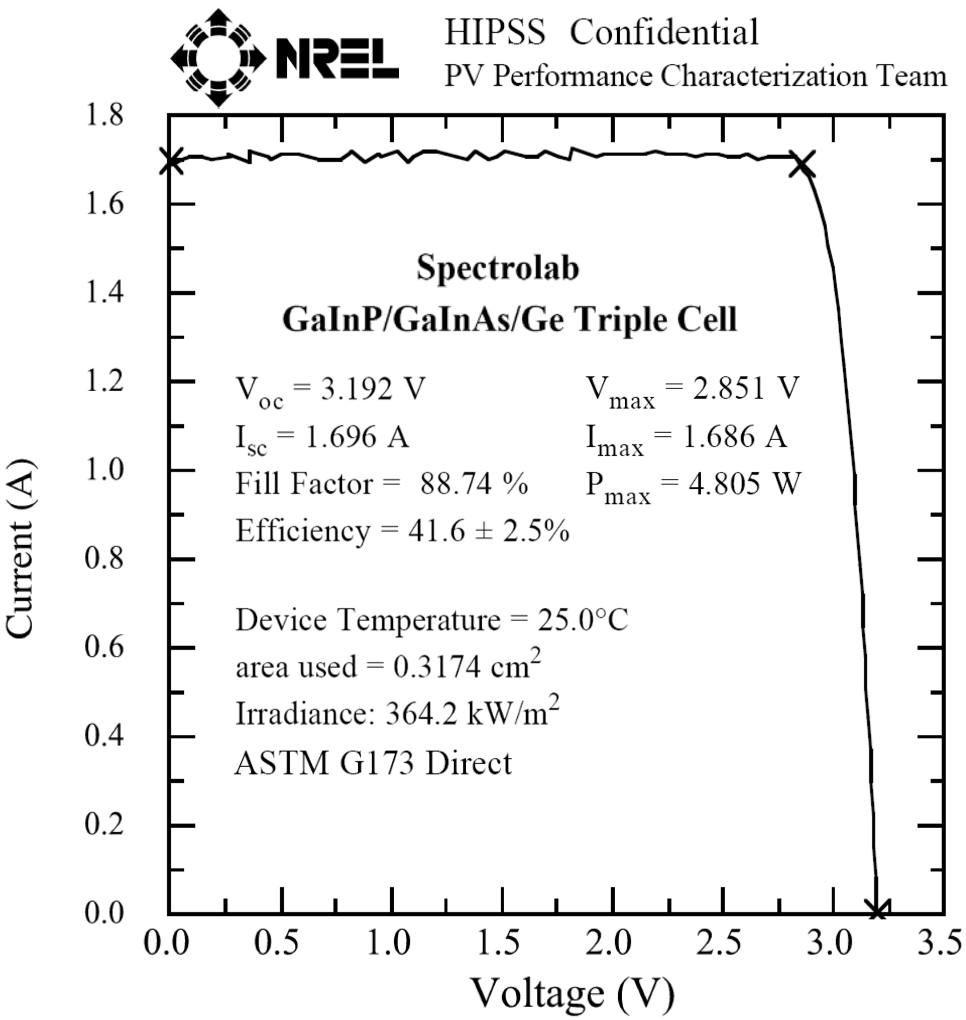

Ref.: R. R. King et al., 24th European Photovoltaic Solar Energy Conf., *Hamburg, Germany, Sep. 21-25, 2009.*

- **41.6% efficiency demonstrated for 3J lattice-matched Spectrolab cell, a new world record**
- **Highest efficiency for any type of solar cell measured to date**
- **Independently verified by National Renewable Energy Laboratory (NREL)**
- **Standard measurement conditions (25°C, AM1.5D, ASTM G173 spectrum) at 364 suns (36.4 W/cm^2)**
- **Lattice-matched cell structure similar to C3MJ cell, with reduced grid shadowing as planned for C4MJ cell**
- **Incorporating high-efficiency 3J metamorphic cell structure + further improvements in grid design**
→ strong potential to reach 42-43% champion cell efficiency

Concentrator cell light I-V and efficiency independently verified by C. Osterwald, K. Emery – NREL

41.6% Solar Cell
Eff., Voc vs. Concentration

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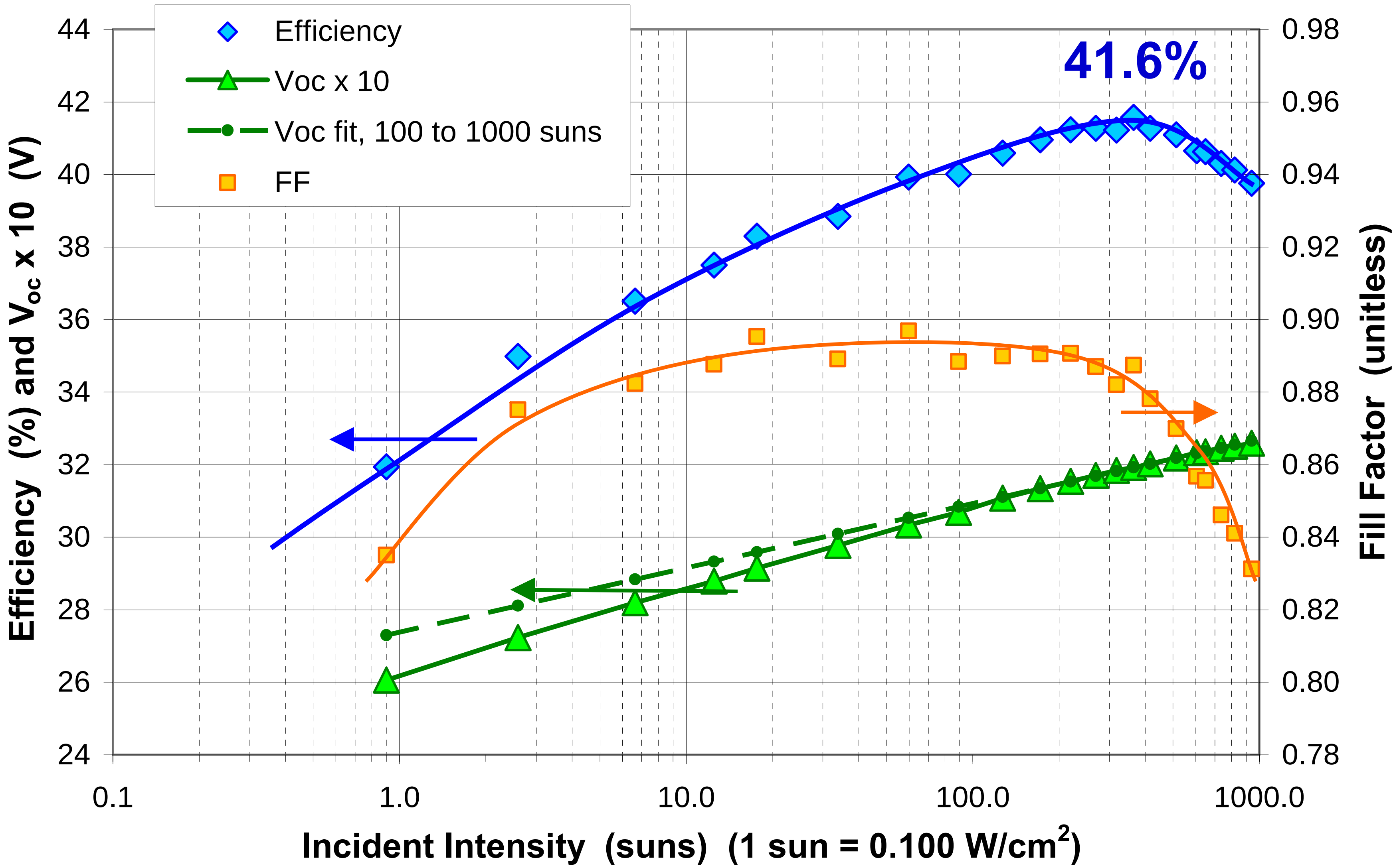

- **At peak 41.6% efficiency → 364 suns, Voc = 3.192 V, FF = 0.887**
- **Efficiency still >40% at 820 suns, at 940 suns efficiency is 39.8%**
- **Diode ideality factor of 1.0 for all 3 junctions fits V_{oc} well from 100 to 1000 suns**

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41.6% Solar Cell LIV Curves vs. Concentration

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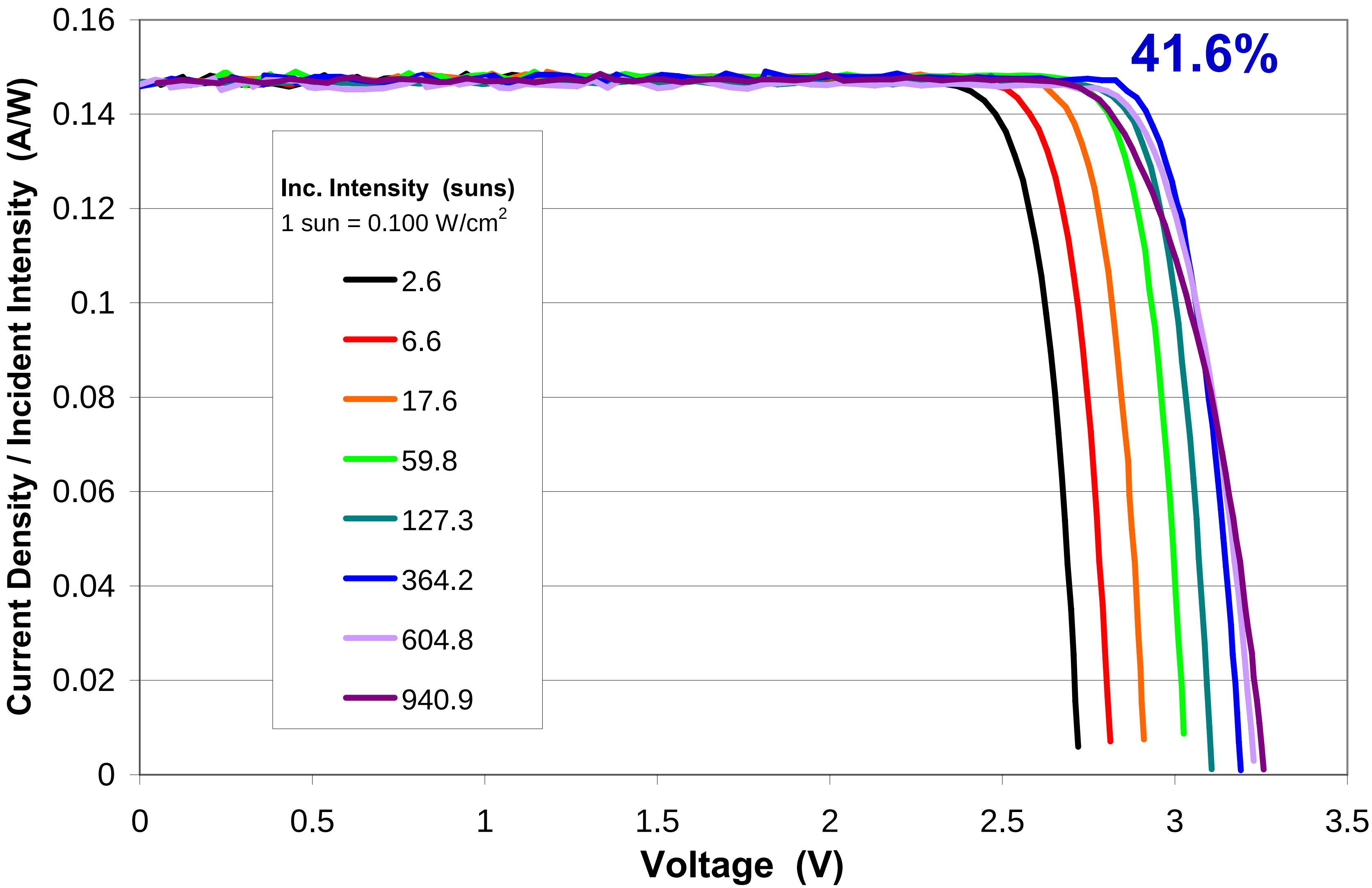

- **At peak 41.6% efficiency → 364 suns, Voc = 3.192 V, FF = 0.887**
- **Series resistance causes drop in V_{mp} above 400 suns, V_{oc} continues to increase**
- **Efficiency still >40% at 820 suns, at 940 suns efficiency is 39.8%**

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Best Research Cell Efficiencies

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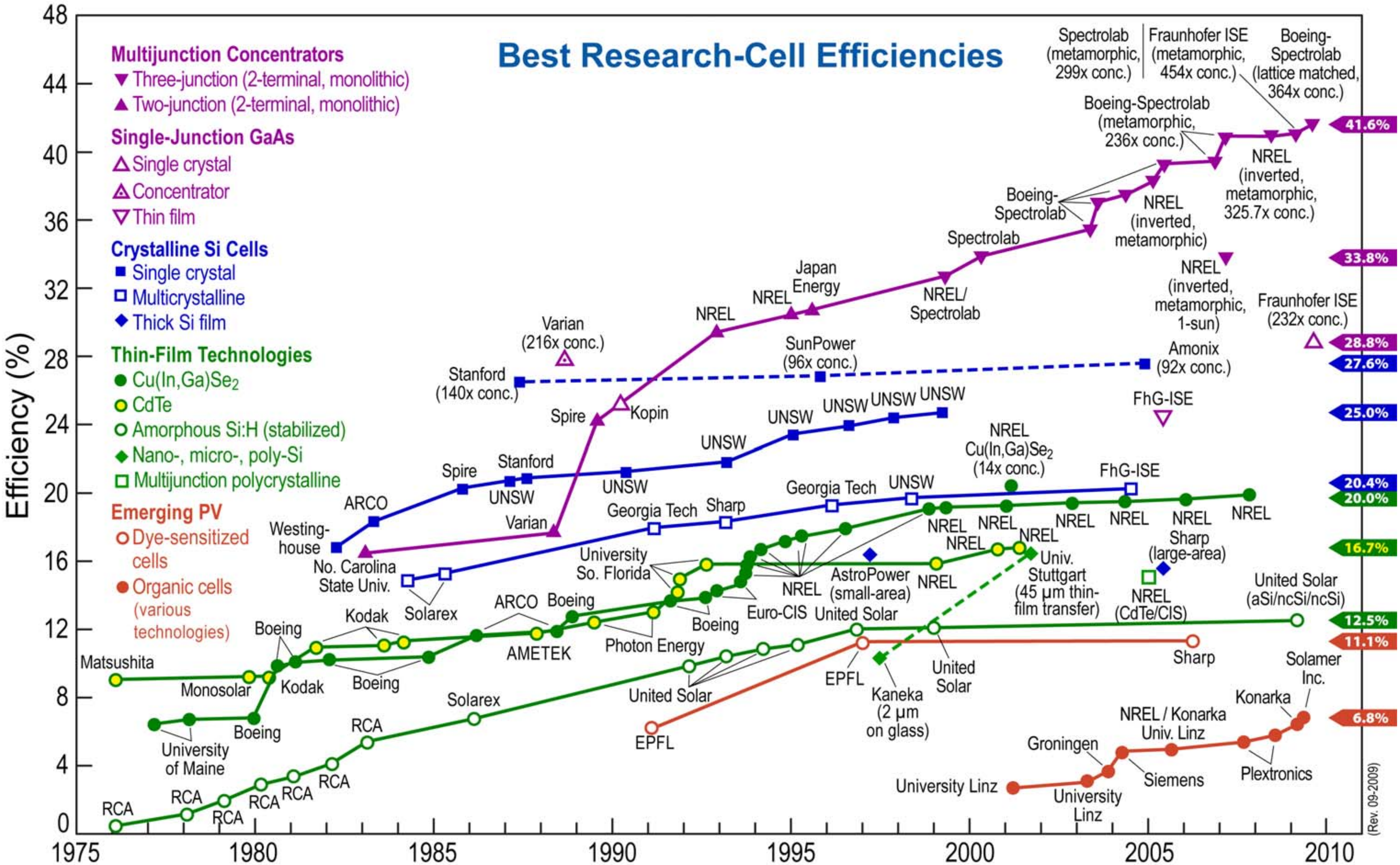

Chart courtesy of Larry Kazmerski, NREL

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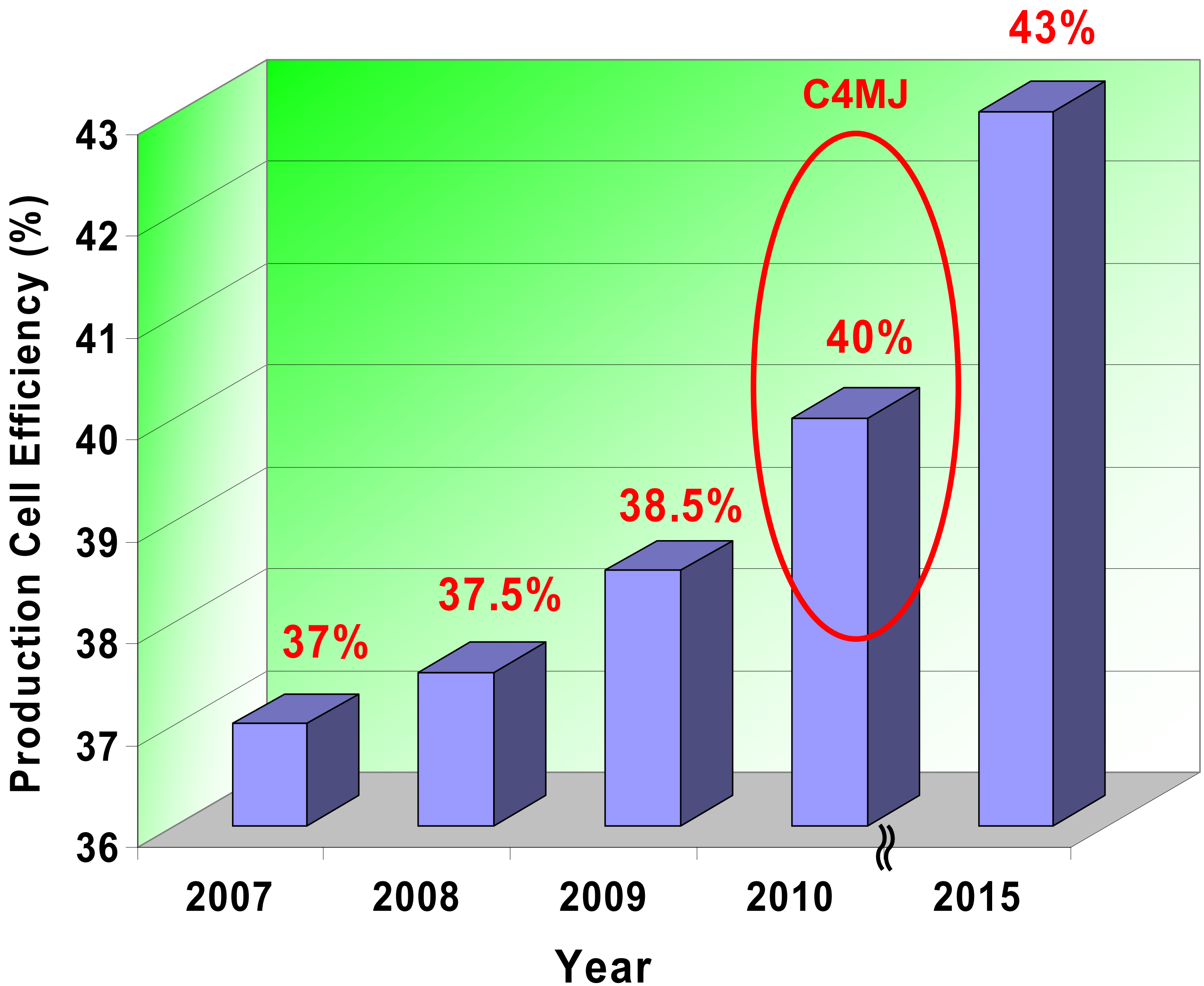
Spectrolab Cell Generations in DOE TPP Program



- Terrestrial concentrator cell efficiency
- Goals in Technology Pathways Partnership (TPP)

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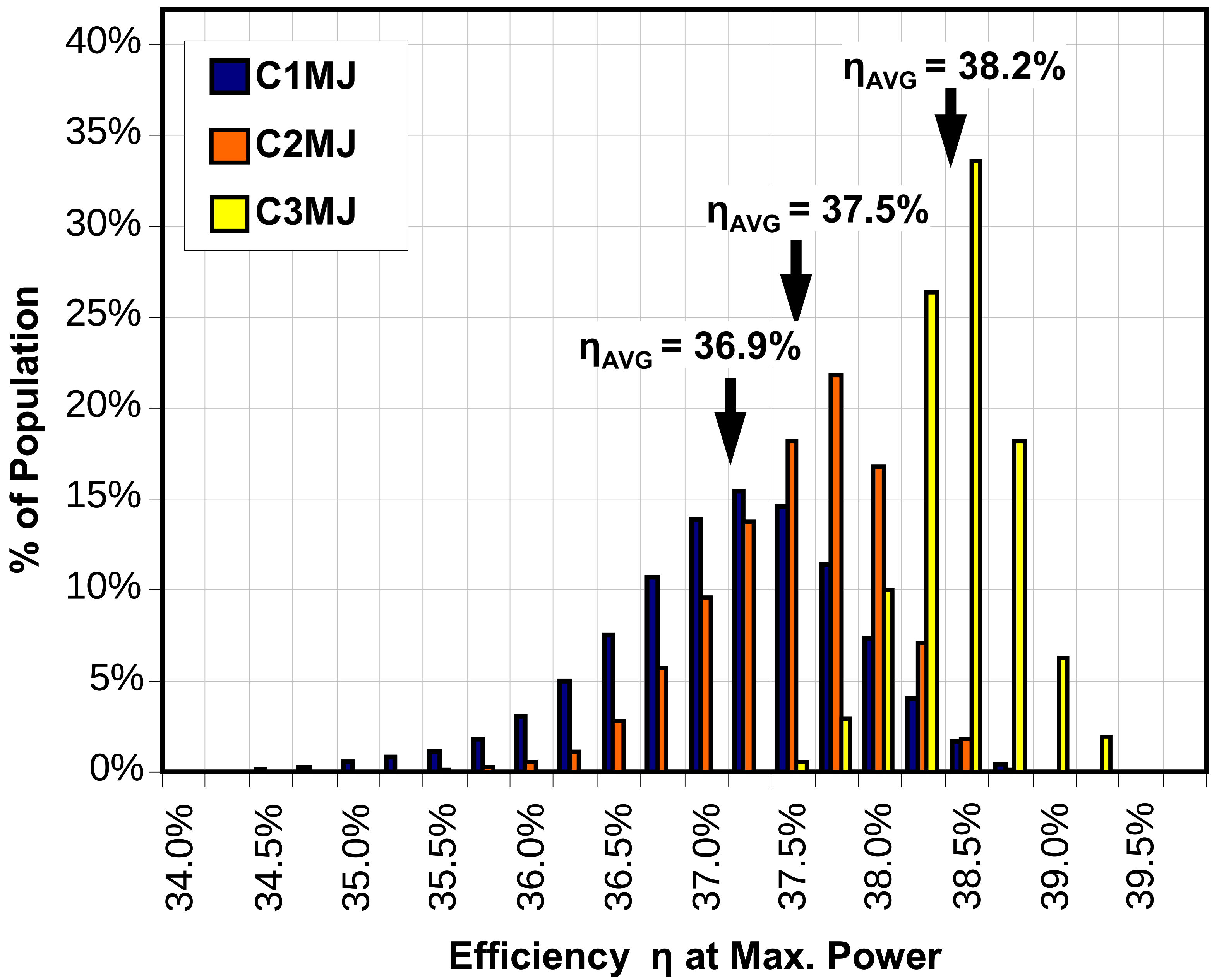
Spectrolab C1MJ, C2MJ, and C3MJ Cell Products



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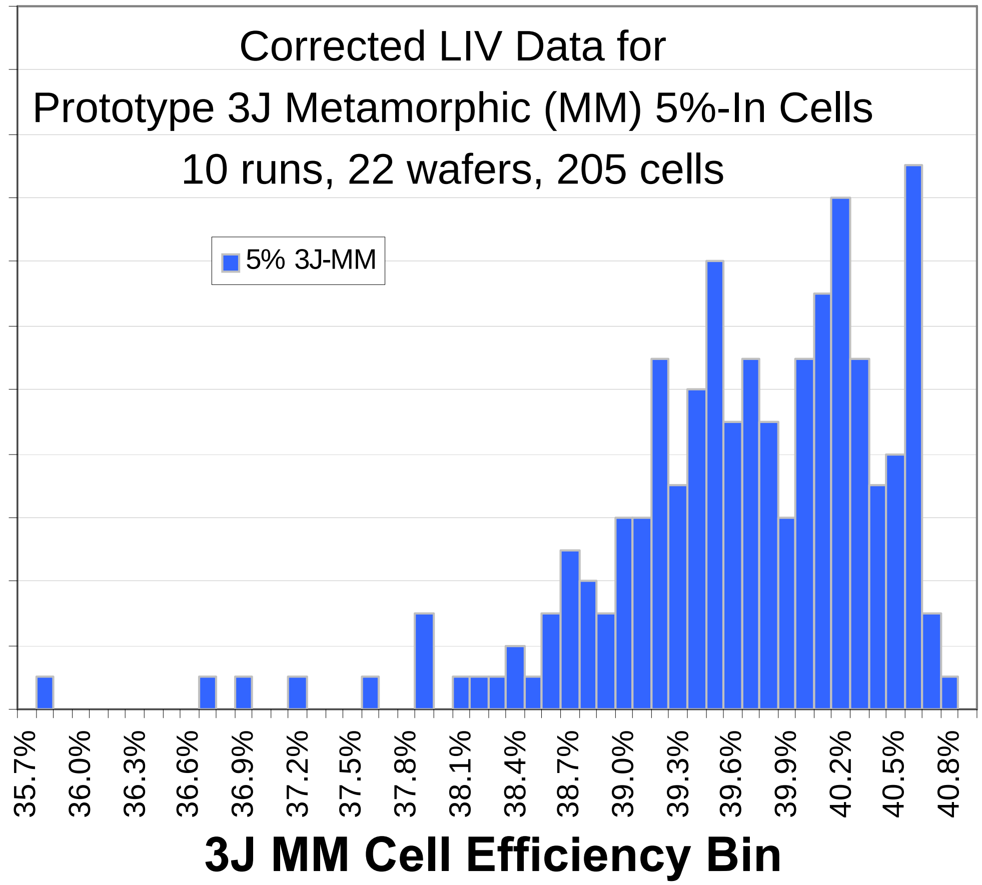
Prototype 3J Metamorphic Cell Builds



	Isc (A)	Voc (V)	FF	Eff
Average	7.601	3.090	0.845	39.6%
Std. dev.	0.135	0.022	0.009	0.8%

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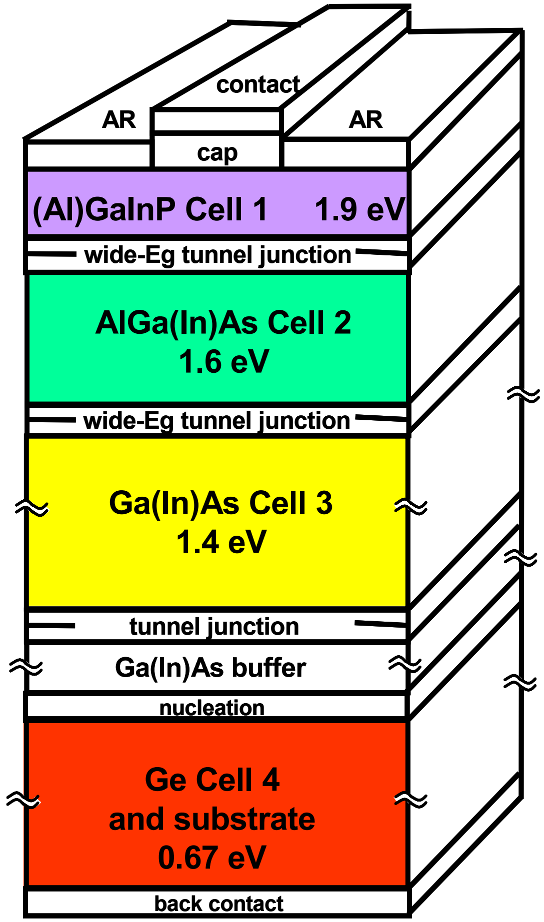
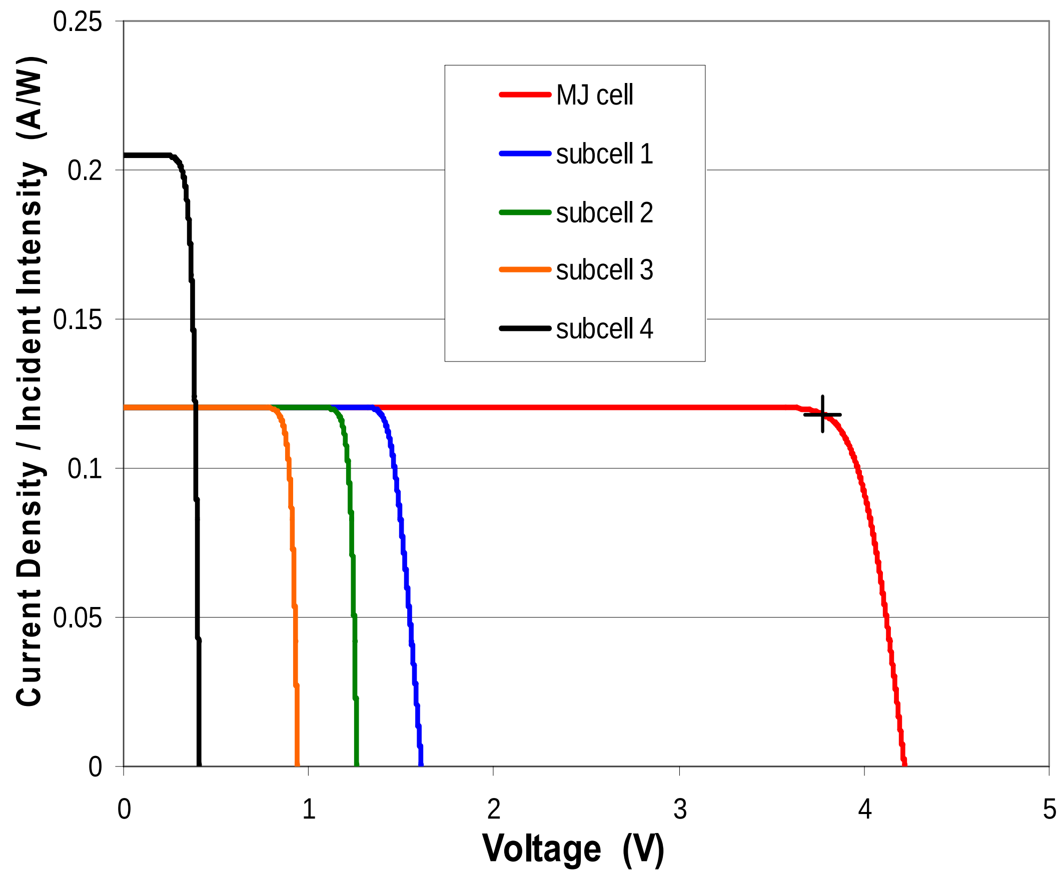
4-Junction Lattice-Matched Cell





- Current density in spectrum above Ge cell 4 is divided 3 ways among GaInAs, AlGa(In)As, GaInP cells
- Lower current and I^2R resistive power loss

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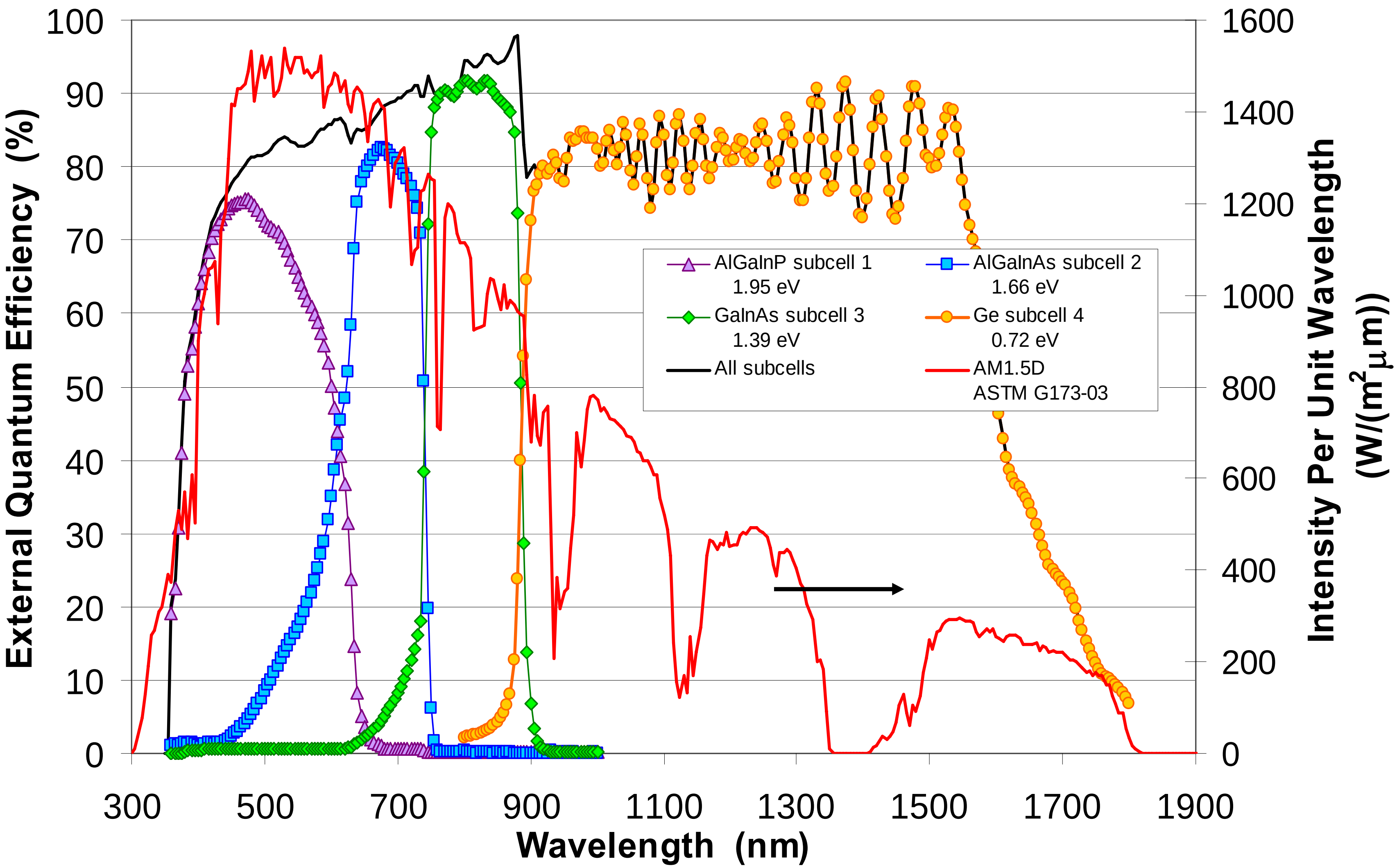
Measured 4-Junction Cell Quantum Efficiency



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Light I-V Curves
Record Efficiency Cells

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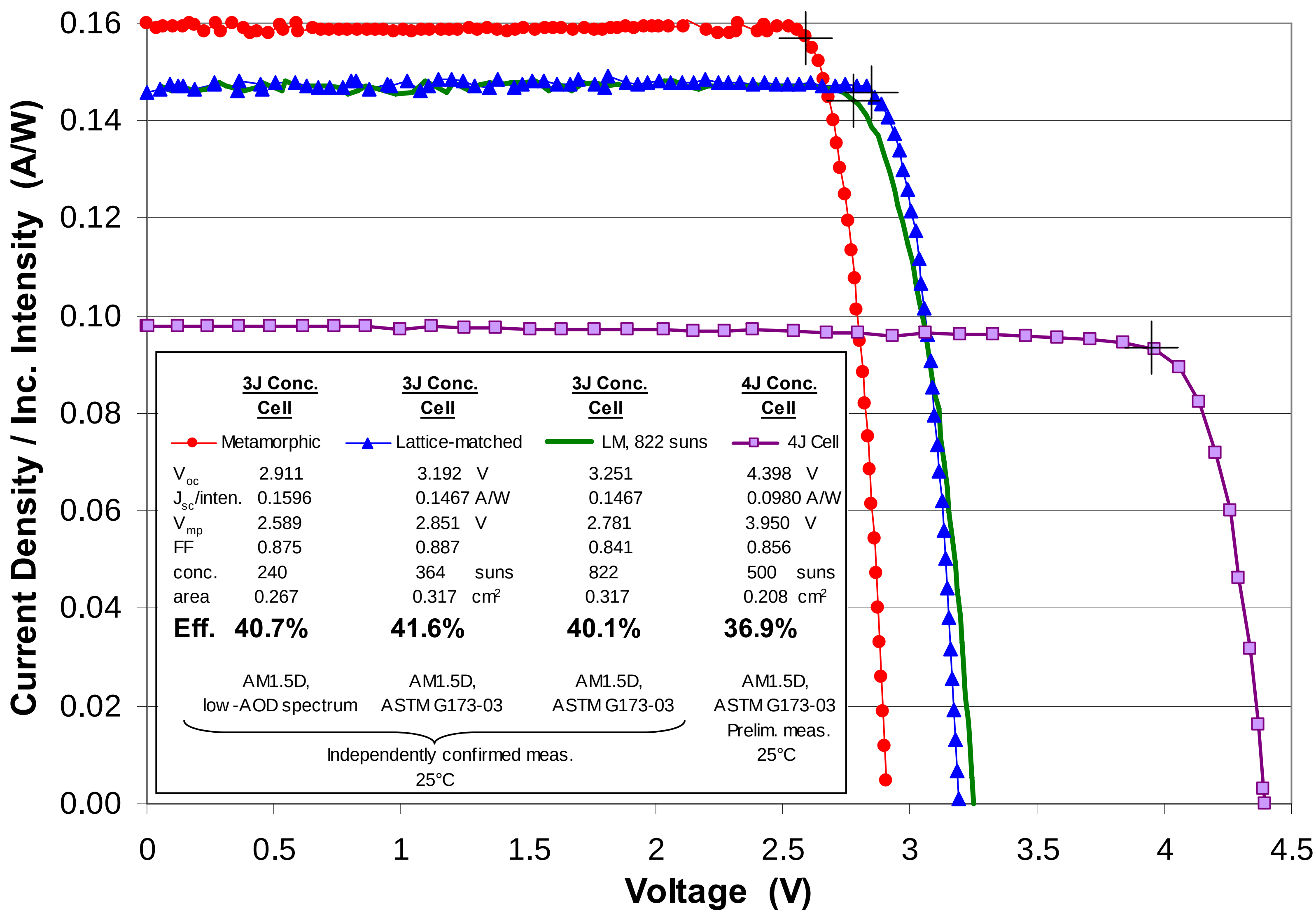

- Light I-V curves for 3-junction upright MM (40.7%), 3J lattice-matched (41.6%), 3J lattice-matched at 822 suns (39.1%), and 4J lattice-matched cell (36.9%)

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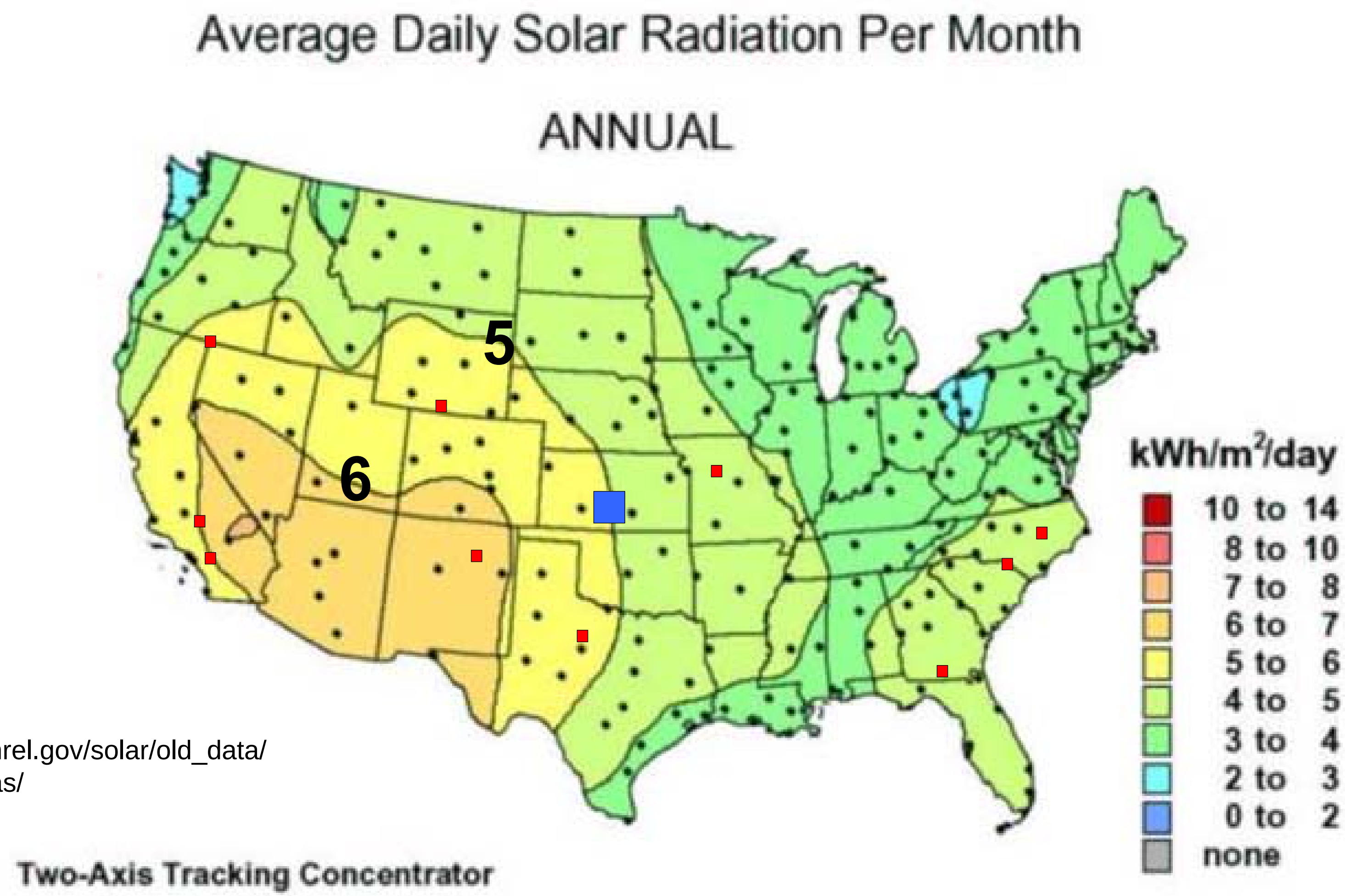
The Solar Resource and CPV Economics

The Solar Resource



Ref.: http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/

- **Entire US electricity demand can be provided by concentrator PV arrays using 37%-efficient cells on:**

150 km x 150 km area of land **or** **ten 50 km x 50 km areas**
or **similar division across US**

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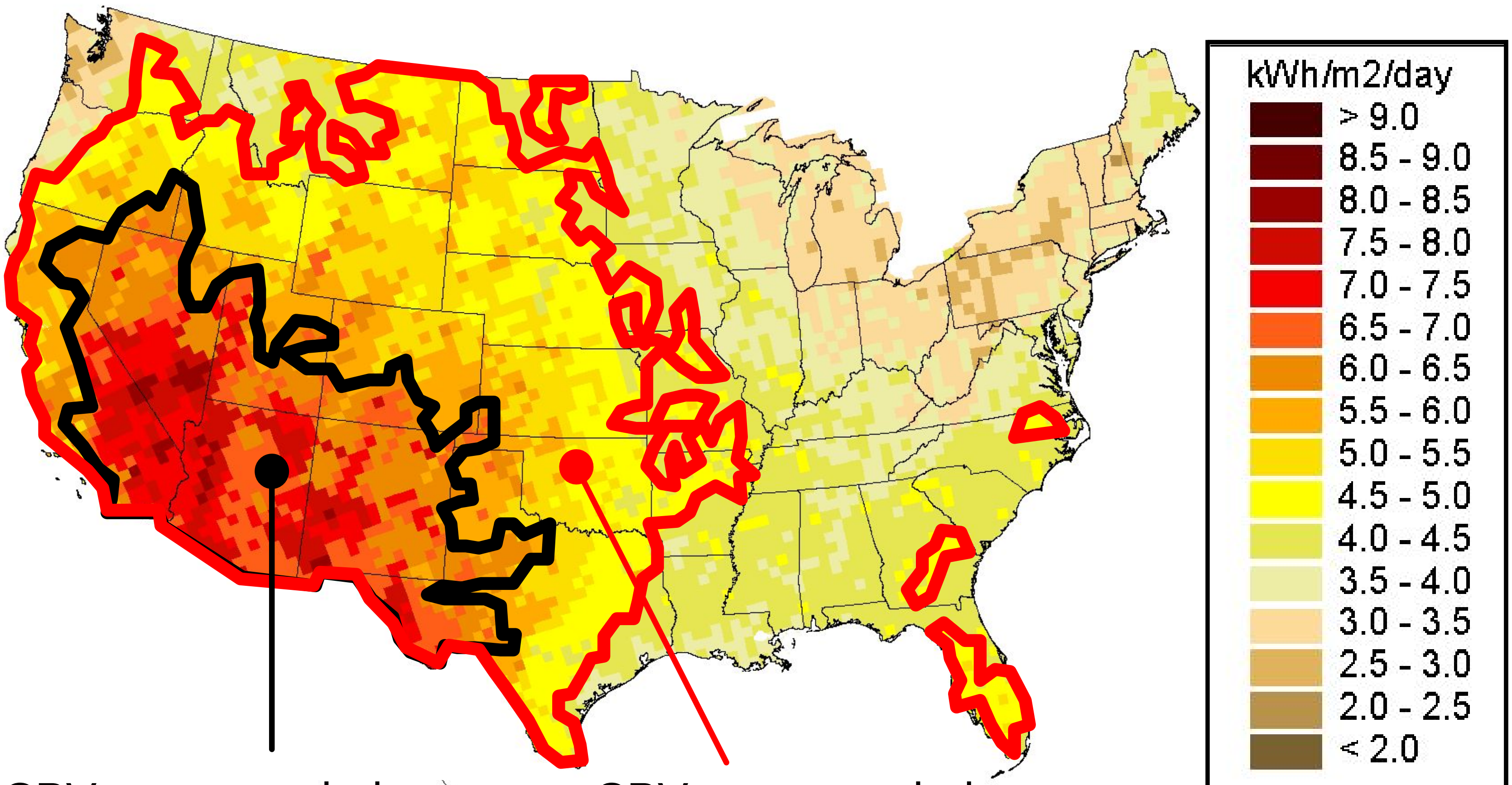
Concentrator Photovoltaic (CPV) Electricity Generation



CPV cost superiority
40% cell efficiency

CPV cost superiority
50% cell efficiency

Map source: http://www.nrel.gov/gis/images/map_csp_us_annual_may2004.jpg

Higher multijunction cell efficiency has a huge impact on the economics of CPV, and on the way we will generate electricity.

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Summary

- **Urgent global need to address carbon emission, climate change, and energy security concerns → renewable electric power can help**
- **Theoretical solar conversion efficiency**
  - Examining built-in assumptions points out opportunities for higher PV efficiency
  - Multijunction architectures, up/down conversion, quantum structures, intermediate bands, hot-carrier effects, solar concentration → higher η
  - Theo. solar cell η **> 70%,** practical η **> 50%** achievable
- **Metamorphic multijunction cells have begun to realize their promise**
  - Metamorphic semiconductors offer vastly expanded palette of band gaps
  - **40.7%** metamorphic GaInP/ GaInAs/ Ge 3J cells demonstrated
  - First solar cells of any type to reach over 40% efficiency
- **New world record efficiency of 41.6% demonstrated**
  - Highest efficiency yet measured for any type of solar cell
  - 41.6% efficiency independently verified at NREL (364 suns, 25°C, AM1.5D)
- **Solar cells with efficiencies in this range can transform the way we generate most of our electricity, and make the PV market explode**